A SIMPLE INTEGRATED MATCHING ELEMENT FOR SIS QUASIPARTICLE MIXERS

A. V. Räisänen,* W. R. McGrath, and P. L. Richards
Department of Physics, University of California
Berkeley, California 94720

and

F. L. Lloyd
National Bureau of Standards
Boulder, Colorado 80303

ABSTRACT

An integrated superconducting microstrip is shown to be a convenient, flexible, and well characterized matching element for a superconductor-insulator-superconductor (SIS) heterodyne mixer. An open-circuited microstrip stub that reflects a parallel inductance across the junction is used to broaden the bandwidth of the RF match of a 30-40 GHz SIS mixer. Measurements with Pb-alloy junctions in a full-height waveguide mixer with fixed mechanical tuning give an instantaneous bandwidth of 10 to 15 percent with a mixer noise temperature T_M(DSB)=10±2.5 K.

I. INTRODUCTION

The superconductor-insulator-superconductor (SIS) tunnel junction quasiparticle mixer has recently surpassed the cooled Schottky-diode mixer as the most sensitive millimeter wave receiver for radio astronomy [1]. However, compared with Schottky receivers SIS receivers often have very narrow instantaneous bandwidth, narrow tuning range, or inconvenient tuning requiring several adjustable elements [1,2]. For spectral line measurements, the narrow bandwidth is not always a critical limitation, but convenient tuning is certainly desirable. A bandwidth broad enough to permit double-sideband operation is desirable for continuum astronomy or other radiometric applications.

The question of the optimum embedding impedance for an SIS mixer has not been fully answered. Many workers [2,3,4] have used a value greater than unity for the product $\omega_S R_N C_J$ of the signal frequency, the normal state junction resistance and the junction capacitance. For this case, the junctions are relatively large, rugged, and easy to fabricate. The large C_J effectively shunts the mixer at harmonic frequencies, but must be tuned out at the signal frequency. This is usually accomplished by an elaborate matching circuit which gives the narrow bandwidth [1,2]. Good performance [5] has also been obtained with $\omega_S R_N C_J < 1$. This condition is met with small junctions which are relatively unreliable and difficult to fabricate. Optimum mixer performance then requires external circuit elements to suppress harmonic frequencies. Recent calculations suggest that excellent mixer performance can be obtained by either approach [6].

Optimization of either type of SIS mixer requires tuning elements external to the junction, but close enough to minimize stored energy. We focus our attention on the mixers with $1 < \omega_S R_N C_J < 10$. An inductance parallel to the junction will readily resonate out the junction capacitance as is shown in Fig. 1(a). The quality factor $Q \approx \omega_S R_N C_J$ of this resonance is low enough that an acceptable bandwidth can be obtained. Although the additional capacitance introduced by the dielectric junction substrate across the waveguide enters the embedding impedance in a more complicated way than the junction capacitance, it is expected that an inductance parallel to the junction will also be helpful in minimizing its effect.

We have employed a simple versatile matching structure consisting of an open-circuited superconducting microstrip which acts as a parallel stub to provide the required inductance across the junction. Such a microstrip can also be used to short circuit the second harmonic response of a mixer. The fabrication of the low impedance microstrip lines required for this work, as well as their integration with SIS tunnel junctions, has been extensively investigated in the context of the Josephson computer [7]. Another approach which successfully provides the required parallel inductance has been recently suggested by D'Addario [8]. Our method of tuning the junction can be readily applied to mixer blocks with both full-height and reduced-height waveguides and also to junctions in quasi-optical structures.

II. THE OPEN-CIRCUITED STUB

The susceptance of an open-circuited transmission line can be written as

$$B_S = \tan(\beta \ell)/Z_0, \quad (1)$$

*Permanent address: Helsinki University of Technology, Radio Laboratory, Otakaari 5A, 02150 ESPOO 15, Finland.

0149-645X/85/0000-0669 $01.00 © 1985 IEEE 1985 IEEE MTT-S Digest

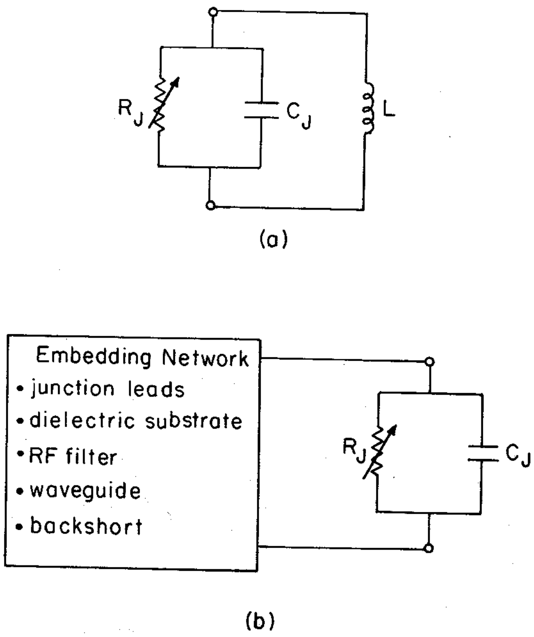

Figure 1 (a) Equivalent circuit of an inductively shunted SIS junction. (b) Important circuit elements in a typical SIS mixer block.

where $\beta=2\pi/\lambda_g$ is the propagation constant on the line, λ_g is the wavelength on the line, ℓ is the length of the line and Z_0 is its characteristic impedance. In order to resonate a total capacitance C at the signal frequency we need

$$\omega_S C + \tan(\beta\ell)/Z_0 = 0. \qquad (2)$$

This can be accomplished with $\pi/2 < \beta\ell < \pi$.

For a superconducting microstrip, Gheewala [7] has given convenient expressions for the inductance and capacitance per unit length of line,

$$L_\ell = \frac{\mu_0}{kw}\left[t_d + \lambda_1 \coth(t_1/\lambda_1) + \lambda_2 \coth(t_2/\lambda_2)\right], \qquad (3)$$

and

$$C_\ell = k\,\varepsilon_r\varepsilon_0\, w/t_d. \qquad (4)$$

Here w is the width of the microstrip, λ_1 and λ_2 are the superconducting penetration depths in the ground plane and the microstrip respectively, t_1 and t_2 are the thicknesses of the ground plane and the microstrip, t_d is the thickness of the insulating layer, ε_r is the relative dielectric constant of the insulating layer, k is a fringing factor, and μ_0 and ε_0 have their usual meaning in SI units. The characteristic impedance of the line is given by $Z_0 = (L_\ell/C_\ell)^{1/2}$, and the wave velocity on the line is $v=(L_\ell C_\ell)^{-1/2}$. Since the RF magnetic field penetrates the region $\lambda_1+\lambda_2+t_d$ which can be significantly wider than the region t_d of RF electric field, the microstrips described here are slow-wave structures.

Several factors must be considered in the choice of a value for Z_0. The line length required to meet the condition in Eq.(2) is minimized by a large value of Z_0. To minimize radiation loss, however, Z_0 must be significantly less than free space or waveguide impedances. However, the orthogonality of microstrip and waveguide fields can also be used to prevent radiation. The Pb-alloy technology that we use employs an evaporated SiO insulating layer with t_d=0.3 μm. If we use linewidths of 3 to 5 μm which are easily fabricated by conventional photolithography, then 10 Ω < Z_0 < 20 Ω which satisfies the radiation loss criterion and gives fringing factors k of 1.2 to 1.4 . Once Z_0 is chosen then the required line length ℓ can be calculated from Eq.(2). Since typical line lengths ℓ>>w, the reference planes for the microstrip are very well defined. The geometry that we have chosen for our SIS mixer junction is shown in Fig.2.

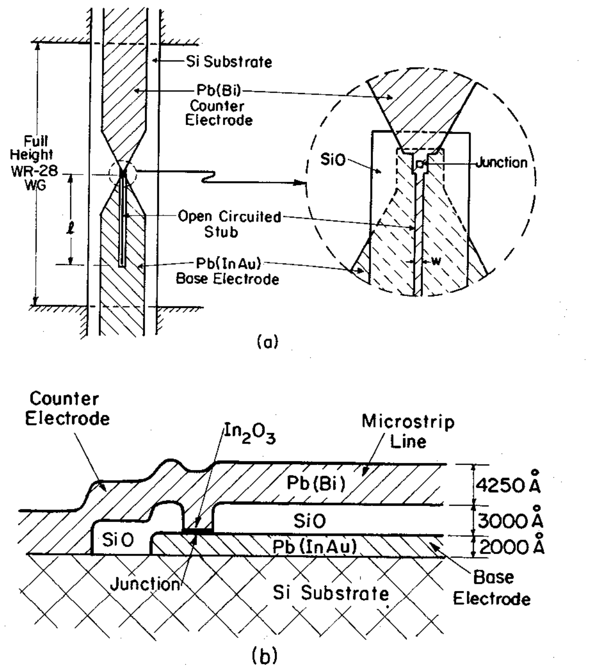

Figure 2. SIS tunnel junction with parallel open circuited microstrip stub shown in top view (a) and cross section (b).

There is a convenient method for characterizing a superconducting microstrip stub coupled to an SIS tunnel junction. Any transmission line has resonances separated in frequency by $\Delta f = v/2\ell$. When the junction is biased at voltage V, ac currents flow at the Josephson frequency $2eV/h$ = 0.484 GHz/μV. These Josephson oscillations excite a wave on the line which is reflected back to the junction where it produces peaks on the dc I-V curve of the junction.

Observation of these resonant modes (Fiske modes [9]) on the dc I-V curve is a convenient way to measure the propagation velocity along the microstrip, and thus to determine whether the correct fabrication parameters have been used. A more detailed discussion of this characterization method will be given elsewhere [10].

III. EXPERIMENTAL RESULTS

Evaluation of the performance of the superconducting microstrip stub has been carried out using a full-height mixer block which has been described previously [2]. In addition to the tuning elements shown in Fig.1(b), it has a screw tuner located $3\lambda_g/4$ in front of the junction. This tuner generally allows a perfect impedance match at ω_S to a single junction SIS mixer [11]. Figure 3 shows the embedding impedance as a function of backshort position at 33 and 36 GHz (a) when the screw tuner is not used and (b) when the screw tuner is adjusted to maximize the gain of a mixer without a stub at 36 GHz. These results were obtained from scaled model measurements at 3 to 5 GHz [11].

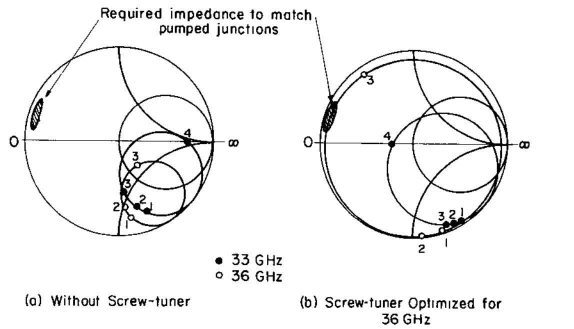

Figure 3. Smith chart plots summarizing measurements of the mixer block made on a large scale model at 3 to 5 GHz. The embedding impedance of the SIS junction is shown as a function of the position of the backshort. The numbers give the separation between the junction and the backshort in arbitrary units (a) without the screw tuner and (b) with the screw tuner optimized for match to an SIS mixer at 36 GHz without a microstrip stub. The shaded region shows the impedance required to match the mixer.

We have used Pb-alloy junctions with area $\approx 8\ \mu m^2$, capacitance $C_J \approx 300$ fF, and normal state resistance $R_N \approx 150\ \Omega$. We thus estimate that $\omega_S R_N C_J \approx 10$ at 36 GHz. The embedding impedance required to match such junctions when pumped with the appropriate local oscillator (LO) power is shown as a shaded region in Fig. 3.

Without either the screw tuner or the microstrip stub, the mixer performance is broadband, but not satisfactory. The double-sideband (DSB) gain measured with a cryogenic hot-cold load [11] is $G_M \approx -10.5$ dB, and the gains of the two sidebands measured with a coherent source are equal within ±2 dB. The DSB mixer noise is $T_M \approx 14$ K. The small value of gain is due to the large impedance mismatch at ω_S.

When the screw tuner and the backshort are both adjusted for optimum gain at one sideband (33 or 36 GHz), we typically measure a single-sideband gain G_M(SSB) ≈ -6 dB. However, the ratio of the gains in the two sidebands is >25 dB in this case. The 3 dB bandwidth is about 200 MHz.

Junctions with parameters similar to those described above, but integrated with the open-circuited microstrip stub illustrated in Fig. 2, were fabricated and tested. The microstrip width was chosen to be w=5 μm. The penetration depths in the ground plane and the microstrip were estimated to be $\lambda_1 = \lambda_2 = 0.135\ \mu m$. The phase velocity was calculated to be v=0.3 c and the line impedance $Z_0 = 10\ \Omega$.

We estimated the optimum stub length for matching the frequency range from 33 to 36 GHz to be $\ell = 1.05$ mm from the embedding impedances shown in Fig. 3 and the value $C_J = 300$ fF. Based on this rough calculation we made junctions with $\ell = 0.9$, 1.0 and 1.1 mm. Measurement of the dc resonant peaks for these junctions gave a phase velocity of

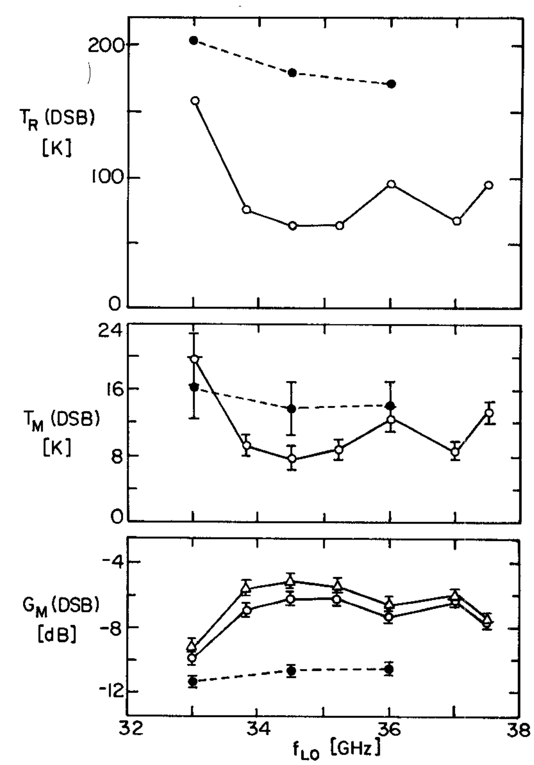

Figure 4. Mixer and receiver performance measured with no screw tuner and no mechanical tuning adjustments. The solid lines are measured with the 1.1 mm microstrip stub, the dashed lines with no microstrip stub. The open circles give the double-sideband mixer gain including reflection at the IF port due to impedance mismatch. The open triangles give the gain when corrected for this mismatch. The IF frequency was 1.5 GHz.

$v/c=0.30\pm0.01$, which is in excellent agreement with the calculated velocity.

We tested each type of stub-tuned junction using the same procedures as for the junction with no microstrip stub. The excellent results obtained with the $\ell=1.1$ mm microstrip stub are summarized Fig.4, and compared with the measurements on a junction with no stub. The curves in Fig.4 show that for this case the microstrip stub increases the gain of this broad band mixer by $\sim$4 dB over a 12 percent bandwidth. Conversion gains measured using junctions with the shorter stubs were smaller by 4-15 dB at an LO frequency of 34.5 GHz. This result suggests that the junction capacitance was closer to 200 fF than our original estimate of 300 fF.

Also shown in Fig. 4 is the double-sideband receiver noise temperature T_R(DSB) measured for our system using junctions with and without the microstrip stub. These temperatures are referred to the position of our RF variable-temperature load [11] on the input to the mixer.

Measurements were also carried out on junctions with and without the microstrip stub, which have been optimized for narrow band operation at 33 and 36 GHz using both the backshort and the screw tuner. Since we believe that the use of both adjustable elements in the mixer block can produce a perfect match for these values of signal frequency, we were surprised to observe that the use of the microstrip stub gives an improvement $\sim$1 dB in narrow band mixer gain, which is only slightly larger than the experimental uncertainties. This improvement could be due to a change in the termination of the image, but also to improved termination at the second harmonic.

IV. CONCLUSIONS

We have demonstrated that an open-circuited superconducting microstrip integrated with the SIS junction provides an easy way to broaden the RF bandwidth of an SIS mixer. Such a stub can also be used to short circuit the second harmonic response of the mixer and thus improve narrow-band response.

Techniques already used for fabricating SIS junctions can be used to make integrated microstrip lines in a reproducible, well characterized way. The resulting tunnel junction can be used in full-height, reduced-height, or open-structure SIS mixers, and in other high frequency applications of superconducting tunnel junctions such as SIS direct detectors, Josephson effect oscillators, and harmonic generators or RF SQUIDS.

ACKNOWLEDGEMENTS

We wish to thank J. Carlstrom, A. Smith and J. Welch for useful discussions, and the Berkeley Radio Astronomy Laboratory for the use of their network analyzer. This work was supported by the U.S. Office of Naval Research under Contract No. N00014-75-c-0496.

REFERENCES

[1] S.-K. Pan, M. J. Feldman, A. R. Kerr, and P. Timbie, "A low-noise 115 GHz receiver using superconducting tunnel junctions," Appl. Phys. Lett., vol. 43, no. 8, pp. 786-788, October 15, 1983.

[2] P. L. Richards, T. M. Shen, R. E. Harris, and F. L. Lloyd, "Quasiparticle heterodyne mixing in SIS tunnel junctions," Appl. Phys. Lett., vol. 34, no. 5, pp. 345-347, March 1, 1979.

[3] W. R. McGrath, P. L. Richards, A. D. Smith, H. van Kempen, R. A. Batchelor, D. E. Prober, and P. Santhanam, "Large gain, negative resistance, and oscillations in superconducting quasiparticle heterodyne mixers," Appl. Phys. Lett., vol. 39, no. 8, pp. 655-658, October 15, 1981.

[4] M. J. Feldman and S. Rudner, "Mixing with SIS arrays," REVIEWS OF INFRARED AND MILLIMETER WAVES, edited by K. J. Button, New York: Plenum, 1983, vol. 1, pp. 47-75.

[5] G. J. Dolan, R. A. Linke, T. C. L. G. Sollner, D. P. Woody, and T. G. Phillips, "Superconducting tunnel junctions as mixers at 115 GHz," IEEE Trans. Microwave Theory Tech., vol. MTT-29, no. 2, pp. 87-91, February 1981.

[6] R. G. Hicks, M. J. Feldman, and A. R. Kerr, "A general numerical analysis of the superconducting quasiparticle mixer," submitted to the IEEE Trans. Magnetics, 1984.

[7] T. R. Gheewala, "Design of 2.5-micrometer Josephson current injection logic (CIL)," IBM J. Res. Develop., vol. 24, no. 2, pp. 130-142, March 1980.

[8] L. R. D'Addario, "An SIS mixer for 90-120 GHz with gain and wide bandwidth," submitted to the Int. J. Infrared and Millimeter Waves, 1984.

[9] M. D. Fiske, "Temperature and magnetic field dependence of the Josephson tunneling current," Rev. Mod. Phys., vol. 36, pp. 221-222, January 1964.

[10] A. V. Räisänen, W. R. McGrath, P. L. Richards, and F. L. Lloyd, "Broad band RF match to a mm-wave SIS quasiparticle mixer," submitted to the IEEE Trans. Microwave Theory Techniques, 1985.

[11] W. R. McGrath, A. V. Räisänen, P. L. Richards, R. E. Harris, and F. L. Lloyd, "Accurate noise measurements of superconducting quasiparticle array mixers," submitted to the IEEE Trans. Magnetics, 1984.